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Analytical Model for the Wide-Strip Rolling Mills Working Rolls Wear-Out Failures

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Abstract

The paper proposes a mathematical model for the gradual shape deterioration of wide-strip rolling mills working rolls active generatrixes subject to wear within the working zone during tandem rolling strips of a specified gauge. While modeling, the authors have determined the theoretical dependency needed to estimate the mean life of working rolls according to the transverse strip gauge interference criterion. Gauge interference of tandem-rolled strip transverse section shall be derived from the sum of the values of current shape of upper and lower working rolls active generatrixes, which are calculated based on strip width. In its turn, an active section of each roll shall be calculated for every following strip as a difference between the current roll radius values at the crown middle and that above/below the strip edge, while the shape deterioration rate of active roll generatrixes shall be defined by the difference between the roll wear rates in these sections. To estimate the rate of roll wear during rolling every following strip of the specified gauge, the base dependency of the structure-energy concept describing wear of stationary tribocouplings is used, which has been obtained by simultaneous solution of fundamental equations of molecule-mechanical and structure-energy friction theories. The moment of working roll failure (expected life) is determined based on the condition of achieving the nominal limit by gauge interference of a current strip.

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Keywords: Failure model; Working rolls; Wear; Transverse gauge interference; Durability; Criterion; Life; Energetic and mechanical approach.

1. Problem statement

The most important task of the theory and practice of flat rolled product manufacture is the issue of forecasting durability of working rolls according to the criterion of limit shape deterioration of their active generatrix due to

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non-uniform wear of crown surface in the working zone. As changes of a current roll shape may be described for the specified rolling schedule with mathematical methods, transverse shape of each strip may be controlled as well as the instant of roll failure (their life) may be forecast based on the time of exceeding the specified value by the transverse gauge interference of the next strip.

Engineering estimate of the roll life according to the known gauge enables their change scheduling, forecasting the mill production output, calculating material removal at redressing, roll consumption and their annual demand as well as analyzing possible methods for increase of their durability and roll product quality

The authors could not find any analytic solutions proposed in the literature. In this connection, they would like to offer a variant of physical and analytical model of working roll failures based on the criterion of transverse shape accuracy degradation at strip rolling.

2. Model of generating working roll failures

The design life of working rolls of any finishing stand at the sheet mill may be determined for an estimated rolling sequence of the j th strip batches with due regard to their shape accuracy and based on the general methodological approach to assessment of parameter reliability of process facilities [1] and corresponding theory of forecasting safety margin and durability of machine parts [2-6].

If in compliance with the above theory, the value of transverse gauge interference of the j th (-nd) strip $\delta_{h\,j}$ is taken as an index of working roll state that undergoes changes at its rolling, the prerequisite of their performance shall be the following inequality in this case:

$$\delta_{h\,j} < \delta_{h\,j*} \tag{1}$$

where $\delta_{h\,j*}$ - the limit of the j th (-nd) strip gauge interference calculated for each stand according to COST requirements to this rolled product size.

The value $\delta_{h\,j}$ of transverse gauge interference of each j th (-nd) strip shall be determined by the sum of values of current shapes of active generatrixes of the upper $\Delta^{u}_{p\,j}$ and lower $\Delta^{d}_{p\,j}$ working rolls that were calculated based on the crown width rater than its length:

$$\delta_{h\,j} = \Delta^{u}_{p\,j} + \Delta^{d}_{p\,j} = \left(\sum_{j=1}^{j*} \Delta^{u}_{p\,(j-1)} + \dot{\Delta}^{u}_{p\,j} \cdot t_j\right) + \left(\sum_{j=1}^{j*} \Delta^{d}_{p\,(j-1)} + \dot{\Delta}^{d}_{p\,j} \cdot t_j\right), \tag{2}$$

where $\dot{\Delta}^{u}_{p\,j}$, $\dot{\Delta}^{d}_{p\,j}$ - rates of changing values of current shape of the upper and lower working roll during rolling the j th (-nd) strip according to its width ($j = 1,2,3,...j*$, $j*$ - the number of the batch at rolling which prerequisite (1) is violated);

$\Delta^{u}_{p\,(j-1)} = \dot{\Delta}^{u}_{p\,(j-1)} \cdot t_{j-1}$ and $\Delta^{d}_{p\,(j-1)} = \dot{\Delta}^{d}_{p\,(j-1)} \cdot t_{j-1}$ - values of shapes of active generatrixes of the upper and lower working rolls after rolling the ($j-1$) -th/-nd strip recalculated for the width of j -th/-nd strip. If $j = 1$, the values $\Delta^{e}_{p\,0}$ and $\Delta^{u}_{p\,0}$ represent shapes of active generatrixes of the upper and lower working rolls according to the width of the first rolled strip $B_{j=1}$. They are obtained when an initial grinding shape is imposed by its distortions from roll temperature and force as well as anti-crossbreak corresponding to conditions of rolling the first ($j = 1$) strip. Thermal profile at cold and hot sheet rolling may be estimated with the known methods of E.A. Garber [7, 8], while roll shape deterioration from roll force and anti-crossback is to be assessed according to methods of V.M. Salganik [9];

$t_j = G_j \cdot /(\rho_j \cdot b_j \cdot h_j \cdot V_{n\,j})$ - time of rolling the j -th/nd strip with G_j weight, $b_j \times h_j$ cross section and ρ_j material density; $V_{n\,j}$ - rate of rolling the j -th/nd strip.

The rate of shape deterioration of active generatrixes of both rolls $\dot{\Delta}^{в}_{p\,j}$ and $\dot{\Delta}^{н}_{p\,j}$ according to the width of the j-th/nd strip under condition (2) may be determined by the difference between the wear rate $\dot{R}_{p\,j}(x)$ of the upper and lower roll at the crown middle ($x = 0$) and above (under) the strip edge ($x = B_j$), correspondingly:

$$\dot{\Delta}^{u}_{p\,j} = \dot{R}^{u}_{p\,j}(0) - \dot{R}^{u}_{p\,j}(B_j)\,;\; \dot{\Delta}^{d}_{p\,j} = \dot{R}^{d}_{p\,j}(0) - \dot{R}^{d}_{p\,j}(B_j)\,. \tag{3}$$

Distribution of wear rates at the upper and lower working roll points across the width of the j-th/nd rolled strip $\dot{R}_{p\,j}(x)$ (according to x coordinate counted from the crown middle) may be calculated with the basic dependency of the energy-mechanical concept of wear of stationary tribocouplings [10-13]. It has been obtained by means of simultaneous solution of fundamental equations of molecule-mechanical [14] and structure-energy [15-17] friction theory and may be presented for thin strip rolling as follows:

$$\dot{R}_{p\,j}(x) = \frac{\alpha^{*}_{p\,j}(x)\cdot \nu_{p\,j}}{u_{e*j}} \cdot \left(\sum_{k=1}^{2} N^{ud}_{mech\,j\,k}(x) + \sum_{k=4}^{5} N^{ud}_{mech\,j\,k}(x) \right), \tag{4}$$

where $\alpha^{*}_{p\,j}(x) = l_j(x)/2\cdot\pi\cdot R_p(x)$ - overlap ratio for section of working roll with coordinate x ; $R_{p\,j}(x)$, $l_j(x)$ - roll radius and length of the deformation zone in section x at rolling the j-th/-nd strip;

$\nu_{p\,j}$ - factor of absorption of external energy by material of surface layer of the working roll to be determined with the known methods of B.V. Protasov [18] in function of its physical characteristics and roughness parameters;

u_{e*j} - critical power content of the working roll material to be determined with the known methods of V.V. Phedorov [16, 19] in function of its thermal-physical and mechanical characteristics;

$k = 1,2,...5$ - number of the section of length partition for elastic-plastic strain area; ($k = 1$ and $k = 5$ - numbers of sections of elastic slipping strip relatively to the roll within the backward and forward slip zone, correspondingly; $k = 2$ and $k = 4$ - number of sections of elastic slipping strip relatively to the roll within the backward and forward slip zone, correspondingly; $k = 3$ - number of section within the adhesion zone, if any) [20];

$N^{ud}_{mech\,j\,k}(x)$ - specific power rating of mechanical power component $\bar{\tau}_{mech\,j\,k}(x) = \bar{p}_{j\,k}(x)\cdot f_{mech\,j\,k}(x)$ acting within the k - th/-nd slipping area of the deformation zone in the roll section with x coordinate during t_j time period:

$$N^{ud}_{mech\,j\,k}(x) = \bar{p}_{j\,k}(x)\cdot f_{mech\,j\,k}\cdot V_{ck\,j\,k}(x)\,; \tag{5}$$

$V_{ck\,j\,k}(x)$ - rate of strip and roll slipping in the k - th/-nd area of the deformation area in the roll section with x coordinate during t_j time period to be determined according to the methods offered by E.A. Garber [20]

$\bar{p}_{j\,k}(x)$ - average pressure in the k -th/-nd area of the deformation zone in the roll section with x coordinate acting within t_j time period:

$$\bar{p}_{j\,k}(x) = \bar{p}_{j\,k}(0)\cdot (q_j(x)/q_j(0))^{0,5}\,; \tag{6}$$

$\bar{p}_{j\,k}(0)$ - average pressure in the k -th/-nd area of the deformation zone in the roll section with $x = 0$ coordinate acting within t_j time period and calculated according to the methods proposed by E.A. Garber [20] for the reduction specified for each stand;

$q_j(x)$, $q_j(0)$ - force per a unit length acting within the deformation zone in the roll section with x and $x=0$ coordinates, correspondingly during t_j time period and determined with the methods by V. M. Salganik [9] with due regard to wear pattern of working and support [21] rolls after rolling the ($j-1$)-th/-nd strip;
$f_{mech\,j\,k}(x)$ - distribution of the values of mechanical component of friction ratio across the strip width (according to x coordinate) within each k - th/-nd area of strip slipping with respect to rolls for t_j time period may be determined:

- within the area of elastic slipping (for $k=1, 5$) - with methods proposed by I.V. Kragelsky [14]:

$$f_{mech\,j\,k} = \frac{(\tau_{0\,p} \cdot \theta_p(T_p) \cdot \alpha_{ef\,p}) + \beta_p \cdot (\tau_{0\,p} \cdot \theta_p(T_p) \cdot \alpha_{ef\,p})^{0,5}}{3 \cdot (\tau_{0\,p} \cdot \theta_p(T_p) \cdot \alpha_{ef\,p})^{0,5} + \beta_p} \tag{7}$$

$\tau_{0\,p}$, β_p and $\alpha_{ef\,p}$ - shear stress of molecular interaction of roll-strip friction pair materials, coefficient of molecular bond strengthening and effective coefficient of hysteresis losses of working roll material [14]; $\theta_p(T_p) = (1-\mu_p^2(T_p))/E_p(T_p)$ - elastic stiffness coefficient, $\mu_p(T_p)$ - Poisson's ratio and $E_p(T_p)$ - elasticity modulus of working roll material to be determined in the function of its temperature T_p according to [7, 8];

- within the area of elastic slipping (for $k=2, 4$) - with methods proposed by M.M. Gornestein [22]:

$$f_{mech\,j\,k} = m_j \cdot \sqrt{\xi_j \cdot R_{\max(p)} / r_{(p)}}\ ; \tag{8}$$

m_j, ξ_j - strengthening factor of contact layer and factor of relative surface approach to be calculated for rolling the j -th/-nd strip [12];
$R_{\max(p)}$, $r_{(p)}$ - roughness parameters of the working roll surface - the maximum profile asperity height and mean radius of point curvature, correspondingly;
The instant of working roll failure shall be determined by violation of performance condition (1), that is, by the moment when current gauge interference $\delta_{h\,j}$ of the j -th/-nd strip achieves the limit value $\delta_{h\,j*}$ that may be reflected with the mathematical equality:

$$\delta_{h\,j} = \left(\sum_{j=1}^{j*} \Delta^u_{p\,(j-1)} + \dot{\Delta}^u_{p\,j} \cdot t_j \right) + \left(\sum_{j=1}^{j*} \Delta^d_{p\,(j-1)} + \dot{\Delta}^d_{p\,j} \cdot t_j \right) = \delta_{h\,j*}\,. \tag{9}$$

Solution of this equation with respect to $t_j = t_{\delta\,j*}$ at $j = j*$ defines the expression for estimation of the design life of working rolls as follows:

$$t_{\delta\,j*} = \left(\delta_{h\,j*} - \sum_{j=1}^{j*-1} \Delta^u_{p\,(j-1)} - \sum_{j=1}^{j*-1} \Delta^d_{p\,(j-1)} \right) / \left(\dot{\Delta}^u_{p\,j} + \dot{\Delta}^d_{p\,j} \right). \tag{10}$$

Hence, the equation system (2) - (10) paying due attention to the dependencies of the above methods provides a model of generating degradation failures of working rolls of the wide-strip mills' finishing stands for estimation of all parameters being integral parts of these equation provided the required level of transverse gauge interference of the rolled strips is ensured.

The software application for calculation of transverse gauge interference of the rolled strips and design roll life based on this model does not require any additional experimental data. All background data are reference records reflecting different material properties, geometry and micro-geometry of rolls and strips as well as set rolling conditions. That is why it enables theoretical studies aimed at estimation of the influence of various factors on roll durability and rolled product quality, analysis and selection of technology and construction solutions ensuring their required level at the project design stage.

3. Conclusion

The proposed model of degradation failures of working rolls has been developed based on the general methodological approach to forecasting reliability of stationary tribocouplings and with due regard to advanced methods for estimation of kinematic, power, temperature and friction parameters of sheet rolling. The obtained equation system enables modeling changes of shape of working rolls subject to wearing within the deformation zone and so cross-section of strips of the known gauge as well as estimation of their design life according to the moment of exceeding the specified value by transverse gauge interference.

Assessment of roll life provides an opportunity to schedule their change and analyze different methods for increasing mill output with simultaneous maintenance of the rolled strip quality.

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